Kissinger

A PROGRAMME OF NUCLEAR POWER

Presented to Parliament by the Lord President of the Council and the Minister of Fuel and Power by Command of Her Majesty February 1955

LONDON
HER MAJESTY'S STATIONERY OFFICE
NINEPENCE NET

Cmd. 9389

[LC)

A PROGRAMME OF NUCLEAR POWER

CONTENTS

[IC)

A PROGRAMME OF NUCLEAR POWER

1. An important stage has been reached in the development of nuclear energy for peaceful purposes. Hitherto the work in this country has consisted of a military programme, a broadly based research and development programme, and the production and use of radioisotopes. The military programme continues to be of great importance but the peaceful applications of nuclear energy now demand attention. Nuclear energy is the energy of the future. Although we are still only at the edge of knowledge of its peaceful uses, we know enough to assess some of its possibilities.

2. Our future as an industrial country depends both on the ability of our scientists to discover the secrets of nature and on our speed in applying the new techniques that science places within our grasp. The exact lines of future development in nuclear energy are uncertain, but this must not deter us from pressing on with its practical application wherever it appears promising. It is only by coming to grips with the problems of the design and building of nuclear plant that British industry will acquire the experience necessary for the full exploitation of this new technology.

3. The application that now appears practicable on a commercial scale is the use of nuclear fission as a source of heat to drive electric generating plant. This comes moreover at a time when the country's great and growing demand for energy, and especially electric power, is placing an increasing strain on our supplies of coal and makes the search for supplementary sources of energy a matter of urgency. Technical developments in nuclear energy are taking place so fast that no firm long-term programme can yet be drawn up. But if progress is to be made some indication must be given of the probable lines of development so that the necessary preparations can be made in good time. A large power station may take five or more years to complete, including finding the site, designing the station and building it. Some of the special materials needed for nuclear power may take several years to get. Moreover, the main burden of building and designing commercial nuclear power stations will fall upon industry who will have to see that the necessary staff are trained. These are some of the many things that must be started soon if we are not to waste precious years in building up this new and unfamiliar industry.

4. Her Majesty's Government have therefore prepared a provisional programme of nuclear power which covers the next ten years in some detail and gives an indication of the probable developments in the following ten years. It will be constantly modified as time goes on and at each stage final decisions will not be taken until the last possible moment so that new technical developments can be used to the fullest advantage.

PART I

THE PROBABLE LINES OF DEVELOPMENT OF NUCLEAR POWER

5. The principle of nuclear fission and the methods by which a nuclear reactor can be used in place of a coal or oil-fired furnace to provide heat for an electric generating plant have been described in various publications.* A short account is given in Annex 1 which also describes

* See particularly "*Harwell: The British Atomic Energy Research Establishment*", London H.M.S.O., 1952, and "*Britain's Atomic Factories*", London H.M.S.O., 1954.

[10]

the experimental nuclear power station now being built at Calder Hall in Cumberland and some of the different types of nuclear power station that might be built in the future. The Calder Hall station is the first attempt in the United Kingdom to produce electricity from nuclear energy on a large scale. Future developments, so far as they can now be foreseen, are likely to be directed at two main objectives: using the main nuclear material, uranium, more efficiently; and reducing the capital cost per kilowatt of a nuclear power station, in terms both of the construction of the reactor and of its initial charge.

6. During the next ten years two types of reactor are likely to be brought into use on a commercial scale. The first type will be similar to those now being constructed at Calder Hall, but improvements in design during the period should enable the later models to show a great advance in efficiency compared with the earlier ones. They will be gas-cooled graphite-moderated "thermal" reactors using as fuel natural uranium or slightly "enriched" uranium, i.e. fuel having a slightly higher fissile content than natural uranium. The first improved models could be designed and built so as to come into operation in about six years' time.

7. These first reactors will burn only a very small proportion of the natural uranium placed in them but they will produce, in addition to heat, the element plutonium which does not occur in nature. This plutonium which can be extracted chemically from the used fuel is potentially very valuable: it is a pure fissile material whereas natural uranium contains only one part in 140 of fissile material.

8. The second type of reactor that may be built for commercial operation during the next ten years is a liquid-cooled "thermal" reactor. This type requires more complicated techniques which at present would result in higher costs. But with further development liquid-cooled reactors should be able to give a much higher heat rating* than the first gas-cooled reactors for the same capital cost. They might therefore eventually prove more economic than the gas-cooled reactors although the comparison will depend on how much the gas-cooled type can be improved. They could take any of several forms (see Annex 1) most of which need "enriched" fuel and could use for this purpose the plutonium produced in the earlier reactors in conjunction with natural uranium. The first commercial liquid-cooled reactors might be built during the latter part of the next ten years and begin operating about 1965.

9. Development after 1965 may take various forms: thorium may be used, at first in conjunction with plutonium, as an alternative fuel; "homogeneous" and "fast breeder" reactors may be developed. It has already been decided to build a full-scale experimental model of a "fast breeder" reactor capable of producing power on a site at Dounreay in Caithness. There is no doubt that the commercial reactor that emerges after these developments as the most suitable, whatever type it may be, will have a lower capital cost per kilowatt and a better utilisation of the nuclear fuel than any of the earlier reactors.

---

* The heat rating of a reactor is the rate of production of heat from each ton of fuel in the reactor.

PART II

THE PROBABLE COST OF NUCLEAR POWER

10. An estimate can be made of the cost of electricity produced by the two types of reactor likely to be in commercial use in the next ten years although it must be subject to a wide margin of uncertainty. Experience of operating reactors at high temperatures and under the high rates of heat extraction required for power is still limited. To the technical uncertainties about the characteristics and performance of the reactors themselves must be added the rather different uncertainties about the supply and value of the nuclear materials required by and produced by a reactor system. In what follows the results of making assumptions on these counts should be regarded as giving only an approximate and not an exact estimate of cost.

Capital and Overhead Costs

11. A reasonably accurate estimate of the constructional cost of the first commercial stations can be made. A station of the same type, but designed to produce fissile material for military purposes as well as electricity, is already being built at Calder Hall at a cost of £15–£20 million. Even the first commercial reactors of the Calder Hall type can be expected to show a higher heat rating than those now under construction, so that the capital cost per kilowatt will be lower. A new station might have an electrical output of 100–150 megawatts or even 200 megawatts. We have no experience on which to base an estimate of the working life of a reactor in a commercial station but a life of between 10 and 20 years seems to be a reasonable technical assumption. As nuclear stations will have a higher capital cost and a lower running cost than other stations they will be run as base-load stations at a high load factor (perhaps 80 per cent).* On these assumptions a rough figure for the annual overhead cost for each unit of output can be calculated. The works and operating costs, excluding fuel costs, can be estimated from the experience of operating coal-fired power stations and the military reactors at Windscale.

12. Developments in reactor design such as the introduction of liquid cooling should gradually lead to much higher heat ratings without much increase in capital cost. This would reduce still further the capital cost per kilowatt and thus reduce the overheads.

Fuel Costs

13. The fuel cost depends on three things: the cost of the raw material, uranium; the processing cost, including the conversion of ore into fabricated fuel elements, the chemical processing of the used fuel elements and the extraction of plutonium from them; and the "level of irradiation", that is, the amount of heat that can be got from each ton of fuel in the reactor before it has to be taken out.

14. Her Majesty's Government consider that enough uranium will be available for the civil programme over the next ten years, after making the best assessment possible of world supplies and of world requirements for all purposes. The cost of the initial charge of fabricated uranium for one of the early types of station similar to Calder Hall may amount to about £5 million;

* The load factor of a station is the ratio of the average load to the peak load carried by the station in each year. The stations having the lowest running costs are operated on the "base load" (i.e., they are used to supply the demand that is present the whole time) and therefore have a high load factor.

a new charge costing the same will be needed every 3–5 years. The cost of processing uranium, both before and after use, is known from the processes now being worked at the Springfields and Windscale factories for the military programme. In the early stages of a power programme the processing costs will be similar, but big reductions can be expected later when new factories are built.

15. It is expected that it will be possible to extract as much as 3,000 megawatt-days of heat from every ton of fuel.* This is the equivalent of the heat from 10,000 tons of coal. There is as yet no practical experience of this level of irradiation at high temperatures and the metallurgical behaviour of the fuel elements is uncertain. But there are many lines of development which should overcome such metallurgical defects as may appear.

The Cost of Electricity and the Credit for the Plutonium By-product

16. Some credit should be allowed for the fissile by-product plutonium. It is in many ways equivalent to uranium 235, another form of fissile material. But plutonium can be extracted by chemical means from a power reactor's used fuel for only a fraction of the cost of separating uranium 235 from natural uranium in a diffusion plant. When concentrated fissile material is available in quantity there will be great scope for the design and development of more advanced and more efficient reactors that need "enriched" material and will not operate on natural uranium. For example, most types of liquid-cooled reactor need "enriched" material; and, looking further ahead, concentrated fissile material in the form of either uranium 235 or plutonium is required for a "fast breeder" reactor or for starting a thorium system. In this manner the early reactors will be producing not only electricity but also the capital equipment (i.e. the initial charge of fissile material) for future power stations. Without the plutonium it would not be possible to build up a system of nuclear power stations of steadily advancing efficiency.

17. In the early stages of an expanding nuclear power programme it is to be expected that concentrated fissile material will be scarce and that if there were a free market its price would be high. It will be required for enriching the fuel charge in new commercial reactors, and also for many experimental and development purposes including the fuelling of prototypes of advanced design. Eventually the system will reach the stage where more plutonium is produced than the new power stations require; its "market" price will then fall and it might be used as a substitute for natural uranium rather than as concentrated fissile material. This is unlikely to happen for 15 or 20 years.

18. It is not obvious what is the right value to put on the plutonium produced, although the effect on the net cost of electricity could be considerable. A high value in the early stages of the programme means a lower net running cost for the early reactors but adds a heavier capital charge on to the later ones, which they might well be able to afford because of their higher efficiency. Limits can be set to the value of the plutonium by considering the uses to which it might be put. At worst it could be fed back into a reactor as fuel in place of natural uranium; and since natural uranium contains only one part in 140 of fissile material, plutonium should be worth at least 140 times as much, weight for weight. At best plutonium is not likely to be worth more than the cost of uranium 235 separated from natural uranium in a diffusion plant. There is a wide range between these limits but both values can be measured in terms of thousands of pounds sterling for a kilogram of plutonium. In the early period it is thought right

* See paragraph 8 of Annex 1.

to allow for the plutonium at a rate of many thousands of pounds a kilogram; the value should eventually fall but would have a significant effect on the cost of generating electricity.

19. On the assumptions set out above, and taking what appears to be a reasonable value for the plutonium, the cost of electricity from the first commercial nuclear stations comes to about 0·6d. a unit. This is about the same as the probable future cost of electricity generated by new coal-fired power stations (see Annex 2 para. 10). If no credit were allowed for the plutonium the cost of nuclear power would be substantially more than 0·6d. a unit. Later stations should show a great improvement in efficiency, but the value of plutonium would probably fall considerably during their lifetime. Even so their higher efficiency should enable them to remain competitive with other power stations.

20. These estimates assume that all the plutonium is used for civil purposes, as would be most desirable. No allowance has been made for any military credits.

PART III

A PROVISIONAL PROGRAMME

21. Her Majesty's Government consider that the development of nuclear power has reached a stage where it is vital that we should apply it commercially with all speed if we are to keep our position as a leading industrial nation and reap the benefits that it offers. The programme outlined below is provisional and must be considered only as the best indication that can now be given of the probable line of development. Types of stations, numbers and dates are all subject to change.

22. Although the decision to go ahead with a nuclear power programme does not depend on precise comparisons of cost, the outline given above has shown that the cost of nuclear power should not be greatly different from the cost of power from coal-fired power stations. This country has a rapidly growing demand for energy, particularly in the form of electric power, and increasing difficulty in producing the necessary quantities of coal. These facts by themselves would justify a great effort to build up a nuclear power system.

23. The stations will be built in the normal way by private industry for the Electricity Authorities,* who will own and operate them. The Atomic Energy Authority, as the only body with the necessary experience, will be responsible for giving technical advice on the nuclear plant. British industry and consulting engineers have as yet no comprehensive experience of nuclear technology. They will be faced with a major task in training staff, in creating the necessary organisation and in designing the stations. This work has already begun. Owing to its complexity and diversity teams drawn from several firms may have to be formed. The preparatory work will call for great efforts from all concerned, and even so it will not be practicable to start building any commercial stations before 1957.

* These are at present the British Electricity Authority, the North of Scotland Hydro-Electric Board and the Northern Ireland Electricity Board. On 1st April 1955 the South of Scotland Electricity Board will come into existence and the Central Electricity Authority will replace the British Electricity Authority.

(10)

24. It is intended that the Electricity Authorities and private industry should obtain as quickly as possible the practical experience in designing and building nuclear power stations that will be the necessary foundation for a big expansion in the later stages of the programme. The Atomic Energy Authority, while giving as much assistance and advice to industry as possible, will remain primarily a research and development organisation and will continue to design, build and operate pioneering types of power reactor. They will also be responsible for buying uranium, fabricating the fuel elements, processing the used fuel and extracting the plutonium from it. There will therefore have to be a continuous process of co-operation and of financial adjustment between the Electricity and Atomic Energy Authorities. The exact arrangements to be made are at present being discussed with them.

Power Stations

25. The provisional programme for the construction of nuclear power stations* is as follows :—

(i) The construction of two gas-cooled graphite-moderated stations (each with two reactors) would be started about mid-1957. These stations should come into operation in 1960-1961.

(ii) The construction of two further stations would be started about 18 months later, i.e. in 1958-1959. These would also have two reactors each and would be similar in type to the earlier two stations but should show an improved performance, particularly in heat rating. Each of the eight reactors in these early stations would have a net output of electricity of 50 to 100 megawatts so that the total output from the four stations, which should all be in operation by 1963, would be somewhere between 400 and 800 megawatts.

(iii) The construction of four more stations might perhaps start in 1960, and then a further four 18 months later, say, 1961-1962. These might come into operation in 1963-1964 and in 1965. It is difficult to specify what type of station these would be, but it is probable that each station would consist of only one reactor, which would be much more highly rated than the reactors in the first four stations. The stations begun in 1960 might be developments of the gas-cooled graphite-moderated type. The last four stations might be of the liquid-cooled type which might by then have been developed sufficiently to be economically satisfactory. The total installed capacity of the eight stations in this group should be well over 1,000 megawatts.

26. The ten-year programme would provide a capacity of about 1,500 to 2,000 megawatts. By the end of the ten years this country would probably be needing new generating capacity at the rate of over 2,000 megawatts a year, and the new nuclear stations coming into operation each year would be meeting something like a quarter of this. On the assumption that nuclear stations would be used as base-load stations they would by 1965 be producing electricity at a rate equivalent to that produced by about 5 to 6 million tons of coal a year. Assuming that the programme continued to expand rapidly, this contribution towards the country's energy needs should also rise rapidly thereafter.

* The term " station " is used here to denote the smallest unit that is likely to be built. In practice more than one such station may be built on the same site.

(1c)

27. The plutonium from the early reactors should begin to become available in 1964 at the rate of several hundred kilograms a year and would be available for enriching the fuel charges in later, probably liquid-cooled, reactors. These reactors would in turn produce plutonium and being more highly rated would produce it more quickly so that it would be available for a rapidly expanding programme of reactors requiring enriched fuel in the late 1960s.

Ancillary Plant

28. The present ancillary plant, which has been built and is used primarily for military purposes, will be adequate at first for a commercial programme of this magnitude but some expansion will be necessary later. A new fuel processing and fabricating plant will be needed in due course in addition to the existing factory at Springfields to meet the rapidly increasing demand for nuclear fuel ; and a new chemical processing plant will eventually be needed to deal with the large quantities of used fuel taken out of the nuclear power stations. Such slight enrichment as may be necessary for the fuel elements in the early stations can be provided from the existing capacity of the diffusion plant at Capenhurst.

Cost

29. The capital expenditure on the construction and installation of the stations in the programme will be considerable. The cost of the first two stations together (comprising four reactors) would probably be between £30 million and £35 million. The next two stations which would have a much higher output would cost perhaps slightly more, while the cost of the last eight stations would be in the region of £125 million in total. The cost of the initial charges of uranium, including fabrication, might amount to a further £40 million. The new ancillary plant that would be required within the 10-year period might cost £30 million. The concurrent capital expenditure on prototype development might be £30 million to £40 million. The cost of the ten-year programme might therefore come to £300 million. The rate of expenditure on the commercial applications of nuclear power would rise steadily during the period and the total over the ten years would amount to more than the £300 million, since it would include expenditure on stations that would not be completed until after 1965 and do not appear in the present programme.

30. This investment will not be a wholly additional demand on the economy. The nuclear power stations will be built instead of other types of station. The investment by the Electricity Authorities in new coal or oil-fired generating capacity over the next ten years would, in the absence of nuclear power, probably be of the order of £1,200 million. With a nuclear power programme there will be a significant reduction in this figure which can be set off against the investment in nuclear power. The National Coal Board should also be able to reduce its investment programme in some ten years time below what would have been necessary in the absence of nuclear power.

31. No accurate assessment can be made so far ahead of the amount of additional investment that the economy will be able to afford. All that can be said is that, given a normal rate of growth of gross national product and given that a reasonable proportion of the increase in resources is made available for an increase in investment, there would not appear to be any great difficulty in accommodating a nuclear power programme on the scale here proposed. It is unlikely that the rate of expansion of investment in the fuel and power industries over the next ten years, even including this programme, will exceed the rate of the expansion in real terms that has taken place since 1948.

[10]

Long-Term Prospect

32. From about 1965 it may be economically desirable to build nuclear power stations instead of coal-fired stations, even without taking account of any long-term difficulties in the supply of coal. Cheap power is a great asset to any industrial country and the more quickly we can convert power generation to the cheaper system the sooner we can hope for a reduction in the real costs of production.

33. On the provisional programme the new nuclear power stations would by 1965 be meeting a quarter of the total requirement of new generating capacity. How quickly it would be possible to expand the programme to match the whole of this requirement will depend upon the progress made in the first ten years. The programme for this first period may be subject to frequent and major change according to the speed of technical development and the success of the early stations. Any attempt to forecast the developments after 1965 must be even more uncertain.

34. The possibilities of expansion will depend to a great extent on the speed with which the necessary techniques are mastered by industry at large. The Atomic Energy Authority will continue to make new information available and to provide training ; with this help industry should acquire wide experience in carrying out a 10 year programme of the type that has been outlined and this would make possible a much greater expansion after 1965. If all went well it might be practicable by the early 1970s to expand the rate of construction of nuclear power stations to match our total requirement of new generating capacity, which by this time might amount to about 3,000 megawatts a year. On this assumption the total nuclear power station capacity installed by 1975 would be of the order of 10–15,000 megawatts, the whole of which could be used for base-load operation. The nuclear power stations would then be producing electricity at a rate equivalent to that produced by about 40 million tons of coal a year.

35. Another possible limitation on the rate of expansion in the later years is the supply of nuclear fuel, particularly the more highly enriched material that will be needed for some of the advanced types of reactor. By the late 1960s the early reactors should be producing plutonium in quantity and this would be available for the later reactors. The provisional programme and the further expansion thereafter will also call for increased supplies of uranium ; and no doubt other countries will be increasing their commercial demands at the same time. Recent evidence suggests that uranium is more plentiful than was once thought ; considerable workable deposits of medium-grade ore are known while the widespread existence of low-grade ores implies that adequate quantities can be produced from them if necessary. Moreover the expansion in the requirement of uranium should be mitigated by the greater economy in its use that will by then have been achieved and by the possible development of the substitute fuel thorium, which should be available in considerable quantities if it is required. For these reasons Her Majesty's Government are confident that the necessary supplies of raw material will be available to meet the increases in demand.

Siting and Safety

36. The history of the development of nuclear energy has made everyone aware of its destructive possibilities and it would be natural to ask whether there were any special dangers associated with nuclear power installations. The first important thing to recognise is that it is impossible for an "atomic

explosion" to take place in a power reactor. If nuclear power facilities are properly designed any accidents that may occur will be no more dangerous than accidents in many other industries.

37. The main hazards in a nuclear power station are caused by the concentration of highly radioactive materials. But these are known dangers which can be guarded against, both by precautions in the design of the reactor itself and if necessary by enclosing some or all of it in a gas-tight container. The reactors that will be built for the commercial production of electricity will present no more danger to people living nearby than many existing industrial works that are sited within built-up areas. Nevertheless the first stations, even though they will be of inherently safe design, will not be built in heavily built-up areas.

38. The disposal of radioactive waste products should not present a major difficulty. The problem is primarily one for the chemical processing plants, which will be few in number, and not for the power stations. The volume of waste will be small and great efforts are being made to determine the most economical methods of storing or disposing of it. There are many valuable uses for it which may be able to absorb a great part of the output. Any material that is discharged will be tested to ensure that it is of extremely low radioactivity, so that it will be harmless and comparable in effect to the natural background radioactivity which is always present.

International Aspects

39. Her Majesty's Government have always been in favour of the greatest possible international co-operation in the peaceful uses of nuclear energy, so that full use can be made of this great new scientific development for the benefit of the world. The Government have recently acted as joint sponsor for the proposal before the United Nations, which has now been approved, to set up an International Atomic Energy Agency and have agreed to make available to the Agency 20 kilograms of fissile material. They intend to play a full part in the international scientific conference on the peaceful uses of nuclear energy that is to be held later this year.

40. Physicists and engineers from a number of countries have taken the opportunity of learning nuclear technology by attending schools and courses in this country such as the Reactor and Isotopes Schools at Harwell. So far as resources permit we intend to provide further facilities for nationals of other countries to attend these schools. Other countries will also be helped to build experimental and development reactors which are an essential preliminary to the building of commercial reactors. We are already helping in this way a number of Commonwealth and European countries.

41. We must look forward also to the time when a valuable export trade can be built up. The experience gained by British industry in designing and building nuclear power stations during the next ten years should lay the foundations for a rapid expansion both at home and overseas. At the moment nuclear power generation is still in the development phase; the exact economics of nuclear power stations are uncertain; and the stations when built will still be pioneering projects and will need much skilled attention. But as time goes on the design of the stations will be improved, the cost of electricity from the stations will be known more exactly and, above all, their construction and operation will have become standard engineering practice. We shall then be in a position to fulfil our traditional role as an exporter of skill, to the benefit both of ourselves and of the rest of the world.

[LC)

PART IV

THE PLACE OF THE PROGRAMME IN THE GOVERNMENT'S FUEL POLICY

42. In a debate in the House of Commons on 9th July, 1954,* the Minister of Fuel and Power, in describing the fuel and power policy of Her Majesty's Government, said that one of its main objectives was to supplement supplies of coal with other kinds of energy—atomic energy as soon as possible and oil forthwith. The previous three Parts of this Paper have given an account of the possible development of nuclear power in this country so far as it can be foreseen now. They express the Government's hopes and views about the scale and timing of the commercial use of nuclear power. It can now be shown how this possible development would fit in with the energy requirements of this country and with the supply of other fuels.

Electricity

43. The use of electricity has grown rapidly in all countries ever since it was introduced commercially in the 1880s. The average increase has been about 7 per cent. a year which means that consumption has doubled every 10 years. This cannot be expected to go on for ever but so far there is no sign that the demand for electricity is even beginning to approach saturation point either in this country or anywhere else, even in countries with a much higher consumption a head than ours.

44. An estimate of the demand for electricity in Great Britain during the next 20 years is given in detail in Annex 2. The demand is expected to continue to grow rapidly although at a slower pace than before. It is likely to be some 3½ times the present level in 20 years' time. To meet this growth in demand, with the opportunity it will offer for higher productivity and efficiency throughout the economy, it is estimated that the installed generating capacity, which averaged 20,000 megawatts in 1954, will have to be increased to 35–40,000 megawatts by 1965 and to perhaps 55–60,000 megawatts by 1975. If the provisional programme suggested above were completed—in practice it is certain to be modified one way or the other—it would provide 1,500 to 2,000 megawatts of nuclear power by 1965 and somewhere between 10,000 and 15,000 megawatts by 1975. The nuclear power stations would be operated on base load and would supply a higher proportion of the total power than the ratio of these figures would suggest.

Coal Supplies

45. Without nuclear power the rate of consumption of coal (or its equivalent as oil) by the power stations alone would increase on the assumption in the last paragraph by perhaps 2½ times over the next 20 years, reaching about 65 million tons a year by 1965 and 100 million tons a year in the 1970s, and would at that time be rising by 4 or 5 million tons a year. On the basis of the provisional programme of nuclear power, the coal required by power stations would level off in the region of 60 to 70 million tons a year during the course of the 1960s. This levelling off in the demand for coal for power stations would come none too soon to help with the difficulties of finding manpower for the mines and of producing at reasonable cost enough coal for the other users of solid fuel whose demand would have been steadily rising meanwhile.

* House of Commons Report. Vol. 529 : No. 145, col. 2517.

[LC)

46. Since the war the production of coal from deep mines has increased from 175 million tons in 1945 to 214 million tons in 1954. But the demands of our expanding home industries have been rising even faster. We have had to supplement output from the deep mines by opencast coalmining and by importing coal, and even so supplies for the householder are still restricted and there is not enough for exports. The National Coal Board have in hand a large programme of capital investment which has gone ahead rapidly in the last year or two; but a great part of this will be needed to maintain the output of the mines at the present level. Greater efficiency in the use of coal and substitution of oil for coal in certain processes including electricity generation will give some limited relief, but the increasing demand for fuel cannot be met without exploiting to the full any new and economic technique available.

47. The provision of enough men for the mines is one of our most intractable problems and is likely to remain so. In order to meet the present demand for coal recourse has been had to voluntary Saturday working as well as to opencast production and to imports: but the demand continues to increase. Any relief that can come from other sources of energy such as nuclear power will do no more than ease the problem of finding and maintaining an adequate labour force. There can be no question of its creating redundancy. The mining industry will in any case remain one of the major employing industries of the country, but it may hope to be relieved by the advent of nuclear power of the excessive strains which are now being put upon it.

PART V

CONCLUSION

48. Our civilization is based on power. Improved living standards both in advanced industrial countries like our own and in the vast underdeveloped countries overseas can only come about through the increased use of power. The rate of increase required is so great that it will tax the existing resources of energy to the utmost. Whatever the immediate uncertainties, nuclear energy will in time be capable of producing power economically. Moreover it provides a source of energy potentially much greater than any that exist now. The coming of nuclear power therefore marks the beginning of a new era.

49. As a leading industrial nation our duty, both to ourselves and to other countries, is to establish this new industry of nuclear energy on a firm foundation and to develop it with all speed. It is a major industrial development that will bring with it revolutionary changes in technique. We shall only learn the new techniques by pressing forward with the practical applications wherever we can and in spite of the many uncertainties surrounding each enterprise.

50. The programme that is described here is provisional and will be altered in many ways in the course of time. But it is hoped that it gives a clear enough picture of the probable scale, scope and timing of developments to put nuclear power in its proper perspective and to show how it will fit in as one of the sources of energy that will be available to meet the rapidly growing needs of our expanding economy.

[1c)

51. The large-scale production of nuclear power cannot be brought about quickly. The first commercial, as opposed to experimental, stations will not be in operation for at least five years. But if proper preparations are made now it will be possible for nuclear power to be produced commercially in significant quantities within ten years. The experience gained from building and operating stations during these ten years should make possible a much more rapid expansion thereafter at home and abroad.

52. New technical developments that cannot at present be foreseen may perhaps lead to a more rapid improvement in the performance of stations than has been assumed. If so we should be in a good position to take advantage of such developments. On the other hand the provisional programme may turn out to be too optimistic: the stations may take longer to design and to build; they may cost more; the amount of development work needed may have been understimated. If any of these things happened nuclear power would come later or be more expensive than the programme suggests. Her Majesty's Government consider that these risks must be accepted.

53. This formidable task must be tackled with vigour and imagination. The stakes are high but the final reward will be immeasurable. We must keep ourselves in the forefront of the development of nuclear power so that we can play our proper part in harnessing this new form of energy for the benefit of mankind.

[LC)

ANNEX 1

THE GENERAL PRINCIPLES OF NUCLEAR POWER

The Nature of Nuclear Reactions

1. Mankind relies at present on two main sources of energy:—

(*a*) Chemical reactions (where energy is released mainly in the form of heat derived from the burning in air of such organic substances as wood, coal, and oil), and

(*b*) naturally occurring movements of large masses of matter (winds, and water falling under gravity).

The source of energy with which we are now concerned is fundamentally different from these forms of energy, although they are all ultimately derived from solar energy, which is itself a product of nuclear reactions taking place in the sun.

2. The atoms of which matter is composed, of which there are about 100 different kinds, are all constructed on the same pattern: they consist of a dense central nucleus which carries a positive charge and is surrounded by a field of negatively charged electrons. The nucleus itself is made up of positively charged protons and uncharged neutrons. The number of protons, which equals the number of electrons, determines the chemical properties of the atom; while the total number of the particles in the nucleus (protons and neutrons) determines its mass. A change in the number of neutrons affects the mass of the atom but leaves its charge (and therefore its chemical nature) unaltered. Chemically identical atoms, that is, atoms having the same charge but different masses, are called isotopes. Uranium 235 and uranium 238 are different isotopes of the same chemical element uranium, the number after the name of the element indicating the mass of the atom, i.e., the total number of protons and neutrons in the nucleus. Isotopes may be stable or they may be radioactive, i.e., tending to change spontaneously into other atoms or isotopes while at the same time emitting particles or radiation. A change in the number of protons, on the other hand, affects the charge of the nucleus and therefore the chemical nature of the atom. The new chemical element produced by such a change may also be stable or radioactive. The radioactivity of different elements plays an important part in nuclear energy.

3. The commonest type of interaction between atoms affects only the electrons; the nucleus remains untouched. Reactions of this kind, of which the burning of coal is one example, are called chemical reactions and the energy they release or absorb is relatively moderate. The energy and heat processes involved in a modification of the nucleus of an atom are about a million times greater. The purpose of nuclear fission or hydrogen fusion is to achieve the release of energy on this scale. A controlled hydrogen fusion reaction is not at present in sight, but the control of nuclear fission is well established.

4. Nuclear fission takes place when a free neutron, the uncharged constituent of the nucleus, is made to strike the nucleus of a fissile element, e.g., uranium 235. The three main results are as follows:—

(*a*) The nucleus splits into two " halves " which fly apart releasing energy which appears as heat.

(b) Several new neutrons are released by the affected nucleus. These can serve a variety of purposes:—

(i) Some of them may collide with other fissile nuclei, repeat the process of fission, and so establish a chain reaction, which can be controlled to provide a continuing release of energy.

(ii) Others may be captured by the nuclei of neighbouring non-fissile atoms, such as uranium 238. This then becomes uranium 239 which is radioactive and changes rapidly to plutonium 239. Plutonium 239, by contrast with uranium 238, is fissile, that is, it will itself undergo fission when struck by a neutron.

(iii) Finally, some neutrons may be a total loss, in the sense that they may be absorbed or lost in ways which make no contribution either to the chain reaction or to the production of fresh fissile material.

(c) The two "halves" into which the original nucleus splits are called fission products. In general they are radioactive and because they are potentially harmful to life and may be destructive of materials it is necessary to keep control of them for a long time; but fortunately their bulk can be made quite small.

5. The heat from the fission of the nuclei can be used to produce steam to drive an electric generating plant. The reactor, i.e. the plant in which fission takes place, is thus the equivalent of the coal or oil-burning furnace of existing power stations.

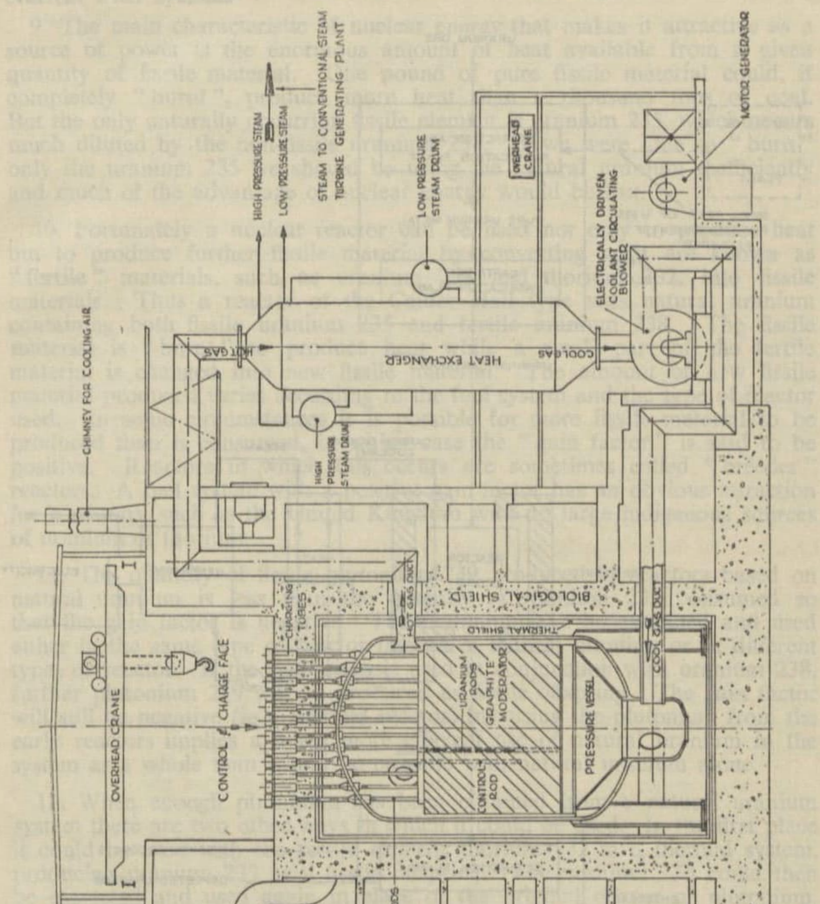
A Typical Nuclear Reactor

6. The practical application of these basic principles can be illustrated by the reactors two of which form part of the experimental power station now being constructed at Calder Hall. This kind of reactor, which is illustrated in Chart I, consists of a mass or core of graphite which is called the moderator. This core is built up from many thousands of separate and accurately machined graphite bricks; it contains numerous vertical channels; and it is enclosed in a pressure shell of steel surrounded by a shield of concrete. The fuel is natural uranium which consists to a small extent (one part in 140) of fissile uranium 235 and to a much greater extent of non-fissile uranium 238. It is fabricated into rods which are sealed in metal cans and placed in the vertical channels within the graphite core; and nuclear fission takes place in these rods, the surplus neutrons emitted travelling about in the graphite and uranium until they produce further fissions or are absorbed to form plutonium or are lost. The heat that is liberated is removed by the circulation of carbon dioxide gas under pressure through the core. The graphite "moderates", or reduces, the average speed of the neutrons produced by the fission reaction to the low value known as the thermal level. A reactor with a moderator is therefore called a "thermal" reactor. If there were no moderator a large proportion of the neutrons would be absorbed by the relatively abundant uranium 238, which captures fast neutrons more readily than does the uranium 235, and the chain reaction would come to an end. The fission process is controlled at a fixed level of activity by moving rods of neutron-absorbing material in or out.

7. As the nuclear reaction proceeds some of the fissile uranium 235 is gradually used up; a small fraction of the uranium 238 is converted by neutron capture into its fissile offspring plutonium 239; structural changes take place in the fuel rods owing to the neutron bombardment to which they

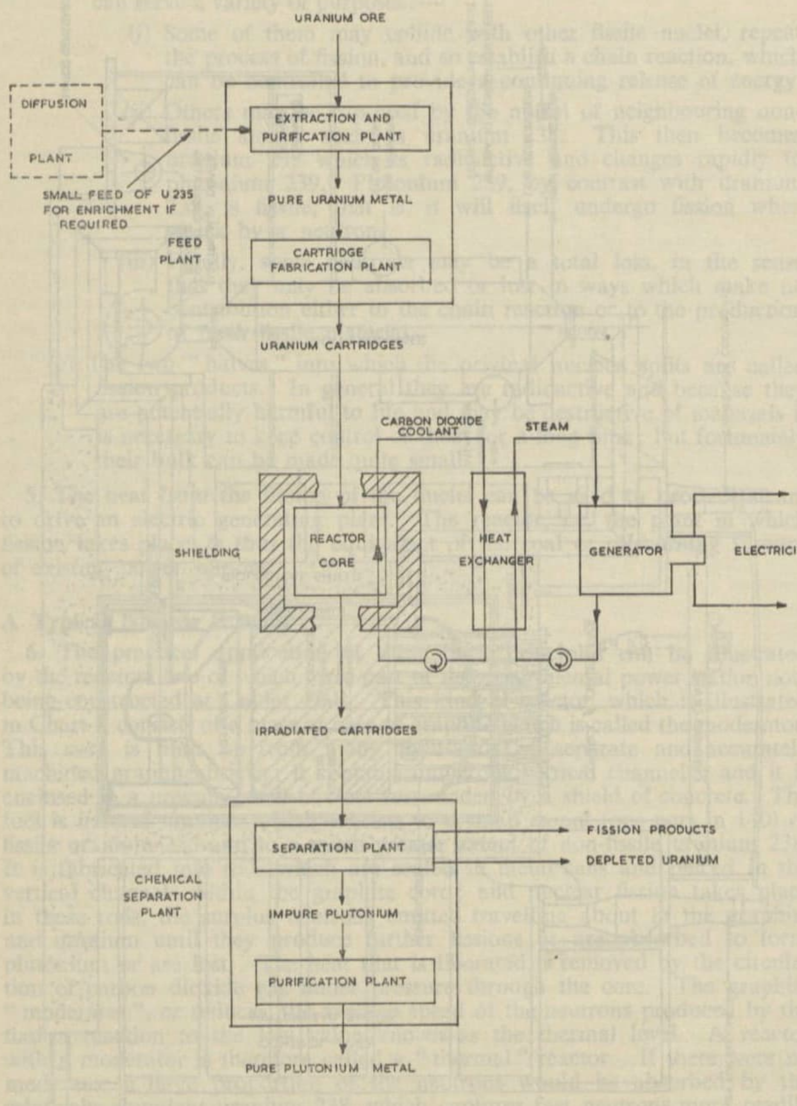
[1c)

Chart I.—A gas-cooled Power Reactor



are subjected ; and fission products accumulate. Eventually the fuel has to be removed and fresh fuel supplied. The irradiated fuel from the reactor has to be chemically processed in order to separate out both the valuable plutonium 239 and the depleted uranium, which now has a smaller proportion of uranium 235 than is present in natural uranium. Chart II illustrates diagrammatically the processes associated with the operation of a Calder Hall type reactor.

Chart II.—Nuclear Power Unit and Ancillary Plant



8. The rate at which the fissile fuel is allowed to burn is expressed in terms of the output of heat, i.e., in megawatts per metric tonne of fuel. The fraction of fuel burnt depends on how fast it burns and how long the fuel element remains in the reactor. If one tonne of fuel burning at a rate of 3 megawatts remains in a reactor for 1,000 days, the level of irradiation achieved is 3,000 megawatt days per tonne (MWD/T).

Nuclear Fuel Systems

9. The main characteristic of nuclear energy that makes it attractive as a source of power is the enormous amount of heat available from a given quantity of fissile material. One pound of pure fissile material could, if completely "burnt", produce more heat than a thousand tons of coal. But the only naturally occurring fissile element is uranium 235, which occurs much diluted by the non-fissile uranium 238. If we were able to "burn" only the uranium 235 we should be using the natural uranium inefficiently and much of the advantage of nuclear energy would be lost.

10. Fortunately a nuclear reactor can be used not only to produce heat but to produce further fissile material by converting what are known as "fertile" materials, such as uranium 238 and thorium 232, into fissile materials. Thus a reactor of the Calder Hall type uses natural uranium containing both fissile uranium 235 and fertile uranium 238. The fissile material is "burnt" to produce heat while a small part of the fertile material is changed into new fissile material. The amount of new fissile material produced varies according to the fuel system and the type of reactor used. In some circumstances it is possible for more fissile material to be produced than is consumed, in which case the "gain factor" is said to be positive. Reactors in which this occurs are sometimes called "breeder" reactors. A fuel system with a positive gain factor has an obvious attraction for a country such as the United Kingdom with no large indigenous sources of uranium or thorium.

11. The quantity of fissile plutonium 239 produced in reactors based on natural uranium is less than the quantity of uranium 235 consumed so that the gain factor is negative. The plutonium can be extracted and used either in the same type of reactor instead of natural uranium or in different types of reactor. If the plutonium is used in conjunction with uranium 238, further plutonium 239 will be produced as fissile offspring. The gain factor will still be negative (in a thermal reactor) but using the plutonium from the early reactors implies a much more efficient use of natural uranium in the system as a whole than would be possible with natural uranium alone.

12. When enough plutonium has been obtained from a natural uranium system there are two other ways in which it could be used. In the first place it could be used with the fertile element thorium 232 in a thermal system, producing uranium 233 as a fissile offspring. The uranium 233 could then be extracted and used again in place of the original charge of plutonium. The gain factor would here be approximately zero, that is about as much uranium 233 would be produced from the thorium 232 as was used up, so that the use of raw material would be highly efficient.

13. Alternatively the plutonium could be used with uranium 238 in a fast reactor system (i.e. a system in which there is no moderator). In this case the gain factor could be made decisively positive so that more plutonium would be produced than was consumed. This would be a big advance in the economic use of nuclear materials.

The Development of Reactors

14. There are four types of atom that can be used as moderator in a thermal reactor: carbon, light hydrogen, heavy hydrogen, and beryllium. Carbon, in the form of graphite, is likely to be the most practical moderator in the immediate future. Light hydrogen in light water (ordinary water) is a possible alternative for reactors producing power on a large scale. These two have obvious advantages over the others from the supply point

of view. A reactor also needs a coolant; and here too a range of possibilities is open comprising at present a gas such as carbon dioxide or helium, heavy water, light water and molten sodium metal. Carbon dioxide and light water are the most probable choices for this country in the next few years.

15. The only reactor for commercial power production that is within our present technical reach in terms of design and construction in the near future is the type now being built at Calder Hall, using graphite as the moderator and a gas, probably carbon dioxide, as the coolant. The first reactors of this type designed specifically for the commercial generation of electricity could be built beginning about 1957, and begin operating in about 1961. The heat rating would be relatively low so that the capital cost for each unit of electricity sent out would be high.

16. The next step in the design of thermal reactors would be to increase the heat rating. Higher ratings should be obtainable from advances in the design of the gas-cooled reactors. Alternatively a liquid could be substituted for a gas as the coolant but this gives rise to more complex technological problems and, unless heavy water is used, requires a higher concentration of fissile material in the fuel than is present in natural uranium. This higher concentration could conveniently be provided by the plutonium produced in the early reactors. These enriched reactors could themselves produce plutonium 239 which could then be used for enrichment in further liquid-cooled reactors, or for starting a thorium system or a fast breeder reactor, or could be fed back into the same reactors instead of natural uranium.

17. A large-scale prototype of a liquid-cooled thermal reactor could probably be constructed and fully tested by about 1963. This might enable commercial reactors of the same type to be completed by about 1965, by which time plutonium would be beginning to come from the early Calder Hall type reactors. One type that could probably be produced on a commercial basis by that date is a light-water reactor, using light water under pressure both as coolant and moderator. Other possibilities are liquid-sodium-cooled graphite-moderated reactors and heavy-water reactors.

18. The design of a thermal reactor might be still further simplified, with a saving in capital cost, if its fissile material were supplied in the form, not of solid metal rods, but of some kind of solution or suspension which could also serve as coolant and moderator. A homogeneous reactor, as this type is called, should also have lower operating costs since there would no longer be any need to fabricate solid fuel elements and encase them in protective material to prevent chemical and corrosive attack by the coolant. It might have a small positive gain factor. It is unlikely that a prototype of a commercial station could be constructed until at least the mid-1960s.

19. In order to obtain breeding of plutonium with a large positive gain factor, a fast reactor will be required, i.e. a reactor without a moderator in which the neutrons are permitted to cause fission of the fuel while they still have a considerable fraction of the energy with which they are born. The small core of a fast reactor presents many difficult technical problems, associated both with heat transfer and with the effect of high temperature on the fuel elements. The solution of these problems will take time. The design of an experimental model of a fast reactor capable of producing power is already in hand. This will be built at Dounreay and will produce data and experience for further developments. A prototype of a commercial station is not, however, likely to be tested until 1965 at the earliest; and production plants could not be expected to be in operation until the 1970s.

(1C)

ANNEX 2

THE PROBABLE DEMAND FOR ELECTRICITY 1955-1975

1. Various methods can be used for estimating the future demand for electricity. One method is to take the past trend in electricity consumption and fit a curve to it which is then extrapolated over the next 20 years. This method subsumes all the main factors which influence the growth of demand. In the absence of any major and sudden change in the structure of the economy, the projection of the curve should provide a reasonable estimate of the size of the demand in 20 years' time. The curve and an extrapolation of it are shown in Chart III.

2. A second method is to make a more detailed analysis of the individual sectors of demand and of the factors which influence their growth. For instance the expansion of industrial demand can be related partly to the expected growth of industrial production and partly to the known trend towards the use of electricity in substitution for other fuels in industry. The forecast of domestic consumption is based on the known trend of the rapid expansion in the use of electricity in the home and on the farm, and on the expected growth in the number of consumers. Similar estimates can be made for the increase in commercial demand and in the demand for traction purposes.

3. These two methods produce much the same result, which is summarised in the following table:—

ELECTRICITY CONSUMPTION IN GREAT BRITAIN

Milliard units (Thousand million kilowatt hours)

	1925	1950	1954 (*Estimated*)	1965 (*Forecast*)	1975 (*Forecast*)
Industrial	3·7	23·4	32·0	61	107
Domestic and agricultural	0·6	14·9	19·6	37	63
Commercial	0·9	6·1	9·5	16	27
Traction	0·5	1·5	1·4	2	4
Total Sales	5·7	45·9	62·5	116	201
Total units sent out (including transmission losses, etc.) ...	6·4	51·9	69·0	130	223

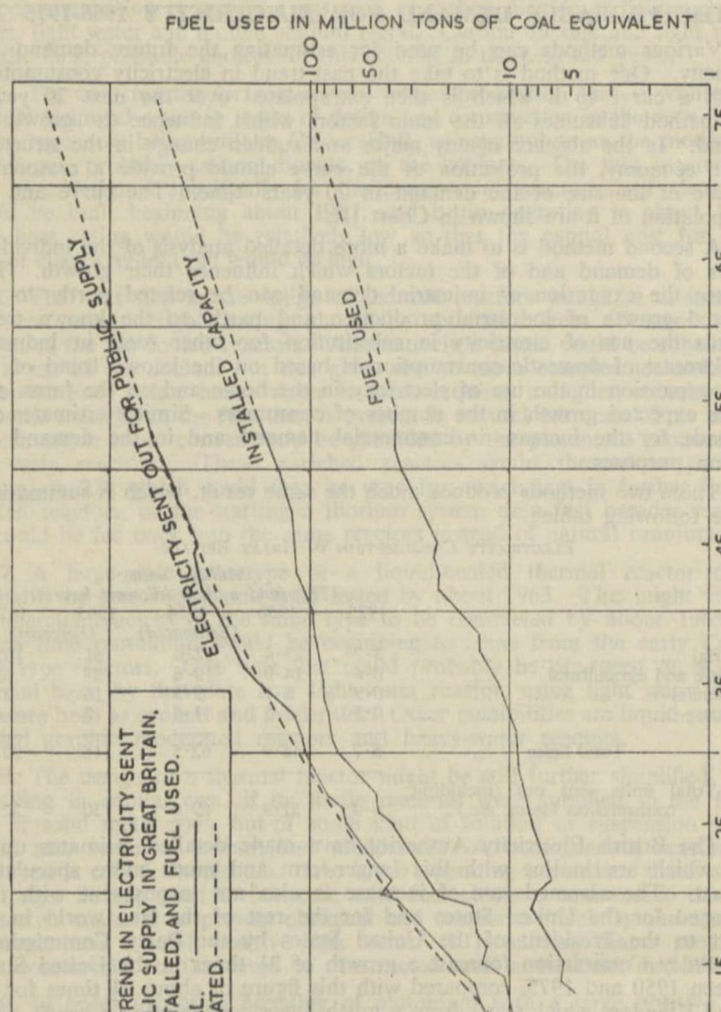
4. The British Electricity Authority have made detailed estimates up to 1960 which are in line with this longer-term and much more speculative forecast. The assumed rate of increase is also not inconsistent with that envisaged for the United States and for the rest of the free world in the report to the President of the United States by the Paley Commission.* (The Paley Commission forecast a growth of 3½ times in the United States between 1950 and 1975, compared with this figure of about 4½ times for the United Kingdom which starts from a much lower consumption a head). The known plans and forecasts of other major industrial countries also assume comparable, or sometimes higher, rates of growth.

5. This forecast is unlikely to be a serious overestimate, and there are good reasons for supposing that it might be conservative. The implied annual rise in industrial production is modest compared with the annual increases that have proved possible since the war; no allowance is made for any significant narrowing of the gap between United States productivity—and electricity consumption—and that of the United Kingdom; and it is possible that full employment will lead to a more rapid rise in consumption than in the period before the war.

* "*Resources for Freedom*," 1952.

(1c)

Chart III.—The Demand for Electricity



[40]

6. Nevertheless the implication of even these conservative estimates is that in about 20 years' time electricity consumption should be running at about 3½ times the present level. The rate of growth, which in recent years has averaged 7 per cent. a year, would on these estimates fall to about 6 per cent. a year in the early 1960s and to about 5 per cent. a year in the early 1970s.

Generating Capacity Required

7. The growth in the industry's capacity over the last 30 years, and the efficiency with which its plant has been used, is illustrated by the following table:—

CAPACITY OF PUBLIC ELECTRICITY SUPPLY SYSTEM

Year	*Capacity installed at end of year (thousand megawatts)*	*Number of units sent out per kilowatt installed*
1925	4·4	1,422
1935	8·1	2,049
1945	12·3	2,853
1950	15·1	3,442
1954	20·7	3,342

In 1954, the industry had an average of 20,000 megawatts of installed capacity, and its maximum available capacity during that year (after allowing for breakdowns, overhauls, &c.) was 80 per cent. of this figure. A further improvement in plant utilisation may be expected through a reduction in the time required for repairs and a closer integration of the system, so that by 1975 it might be over 85 per cent. The average load factor in 1954 was 49 per cent. : and some improvement may be possible, perhaps raising it to 52 per cent. by 1975.

8. On these assumptions the total generating capacity required in 1975 would be of the order of 57,000 megawatts installed. Allowing for some 2,000–4,000 megawatts of hydroelectric and pumped-storage plant and for 10,000 megawatts of existing plant still in operation, this implies the installation in the next 20 years of new plant equivalent to about 45,000 megawatts installed, or 40,000 megawatts sent out—a programme which, on the basis of coal-fired power stations alone, would cost about £2,500 million. On the present B.E.A. programme the capacity installed each year should already have reached about 2,000 megawatts sent out by 1960 ; on the forecasts used here it might well have to exceed 3,000 megawatts sent out during the 1970s.

Coal Required for Power Stations

9. The thermal efficiency of coal-fired power stations has improved rapidly in the last few decades, as the following table shows:—

EFFICIENCY OF STEAM STATIONS OF THE PUBLIC ELECTRICITY SUPPLY SYSTEM

Year	*No. of lb. of coal used per unit generated*
1925	2·43
1935	1·54
1945	1·42
1950	1·37
1954	1·26

The figure for 1954 corresponds to an average thermal efficiency of about 23·6 per cent. The best modern stations already have a thermal efficiency of of 30 per cent., and it is possible that the average efficiency in 1975 might

[LC]

be as high as 30–32 per cent. On the basis of the figures given above and if the calorific value of the coal used by the industry continues to be no less than it is now, the total fuel equivalent required by the power stations would be about 65 million tons in 1965, and might rise by 1975 to a figure in the region of 100 million tons. A proportion of this coal is expected to be replaced by oil; but in round terms it may be assumed that 20 years hence, in the absence of nuclear power, the power stations would be consuming about 100 millions tons of coal, i.e., about 2½ times as much as at present, and twice the 50 million tons now estimated for 1960. By 1975 the rate of consumption might be rising by about 4–5 million tons a year.

The Cost of Generating Electricity

10. The cost of generating electricity in a modern coal-fired power station, operating at a high load factor and having a thermal efficiency of about 30 per cent., is about 0·6d. a unit, made up as follows:—

	Pence per unit
Fuel cost (including handling)	0·38
Other costs including interest and depreciation	0·22
	0·60*

How this will vary in the next ten or twenty years is uncertain but on balance it seems unlikely that the cost of electricity will show any great change compared to other prices. It is possible that the pressure on coal supplies will tend to force up the price of coal used by power stations. On the other hand new stations will be more efficient so that less coal will be required for each unit, and there will be other developments that should also reduce costs. Examples are: bigger generating units, simpler buildings, higher temperatures and pressures in the boilers and higher load factors. It seems reasonable to assume for practical purposes that the cost of generating electricity from new coal-fired stations used as base-load stations will continue to be in the region of 0·6d. a unit.

* The average cost of supplying the consumer is about 1·3d. a unit which includes the cost of transmission and distribution and also the higher cost of operating the less efficient stations at peak periods.

PRINTED AND PUBLISHED BY HER MAJESTY'S STATIONERY OFFICE

To be purchased from

York House, Kingsway, LONDON, W.C.2 423 Oxford Street, LONDON, W.1

P.O. Box 569, LONDON, S.E.1

13a Castle Street, EDINBURGH, 2 109 St. Mary Street, CARDIFF

39 King Street, MANCHESTER, 2 Tower Lane, BRISTOL, 1

2 Edmund Street, BIRMINGHAM, 3 80 Chichester Street, BELFAST

or from any Bookseller

1955

Price 9*d* net

PRINTED IN GREAT BRITAIN

(30728) Wt. 1418—1216 K80 2/55 D.L.